NeoBiota 74: 129–154 (2022)
doi: 10.3897/neobiota.74.83312
https://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Scanning the horizon for invasive plant threats using a data-driven approach

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Academic editor: Curtis Daehler | Received 8 March 2022 | Accepted 19 June 2022 | Published 15 July 2022

Citation: Kendig AE, Canavan S, Anderson PJ, Flory SL, Gettys LA, Gordon DR, Iannone III BV, Kunzer JM, Petri T, Pfingsten IA, Lieurance D (2022) Scanning the horizon for invasive plant threats using a data-driven approach. NeoBiota 74: 129–154. https://doi.org/10.3897/neobiota.74.83312

Abstract

Early detection and eradication of invasive plants are more cost-effective than managing well-established invasive plant populations and their impacts. However, there is high uncertainty around which taxa are likely to become invasive in a given area. Horizon scanning that combines a data-driven approach with rapid risk assessment and consensus building among experts can help identify invasion threats. We performed a horizon scan of potential invasive plant threats to Florida, USA—a state with a high influx of introduced species, conditions that are generally favorable for plant establishment, and a history of negative impacts from invasive plants. We began with an initial list of 2128 non-native plant taxa that are known invaders or crop pests. We built on previous invasive species horizon scans by developing data-based criteria to prioritize 100 taxa for rapid risk assessment. The semi-automated prioritization process

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included selecting taxa "on the horizon" (i.e., not yet in the target location and not on a noxious weed list) with climate matching, naturalization history, "weediness" record, and global commonness. We derived overall invasion risk scores with rapid risk assessment by evaluating the likelihood of each of the taxa arriving, establishing, and having an impact in Florida. Then, following a consensus-building discussion, we identified six plant taxa as high risk, with overall risk scores ranging from 75 to 100 out of a possible 125. The six taxa are globally distributed, easily transported to new areas, found in regions with climates similar to Florida's, and can impact native plant communities, human health, or agriculture. Finally, we evaluated our initial and final lists for potential biases. Assessors tended to assign higher risk scores to taxa that had more available information. In addition, we identified biases towards four plant families and certain geographical regions of origin. Our horizon scan approach identified taxa conforming to metrics of high invasion risk and used a methodology refined for plants that can be applied to other locations.

Keywords
certainty, consensus building, Florida, horizon scan, invasion, prevention, rapid risk assessment

Introduction

Invasive species can negatively impact ecosystems, economies, and human health (CBD 2009). Managing potential impacts of invasive species, and invasive plants in particular, is daunting given the many species introduced to novel areas each year, with rates predicted to increase in the future (Seebens et al. 2017). When governments and private landowners take action, they often manage invasive plants and mitigate negative impacts after establishment. However, preventing the introduction and initial spread of invasive plants is generally more effective and avoids potential ecological and economic losses (Keller et al. 2007; Sheley et al. 2015). Unfortunately, the benefits of prevention are difficult to quantify and involve high uncertainty, making post-invasion control the more common approach (Finnoff et al. 2007; Early et al. 2016). Thus, programs that help identify which non-native plant taxa have a high probability of becoming problematic invaders are essential for providing the first line of defense against plant invasions.

Horizon scanning is the systematic search to identify potential threats, emerging issues, and opportunities that can inform research and action (Sutherland and Woodroof 2009; Amanatidou et al. 2012). The goal of horizon scanning in conservation science is to preemptively identify threats so researchers can provide timely and informed input on policy and decision-making (Sutherland and Woodroof 2009). In Europe, horizon scanning of emerging invaders has involved acquiring lists of potentially invasive species for a specific region, assessing the likelihood of arrival, establishment, and impact for each species, and, in some cases, building consensus among experts around a list of species ranked by risk (Parrott et al. 2009; Matthews et al. 2014; Roy et al. 2014; Gallardo et al. 2016; Lucy et al. 2020). These horizon scans have informed policy and guided resource allocation towards research and prevention efforts.

Florida is one of the most important states for regulating invasive plants in the United States because nearly 85% of all non-native plants imported to the contiguous

United States enter through one of Florida's shipping ports or airports (Gordon and Thomas 1997). As international trade continues to grow, so too does the frequency of intentional and accidental introductions (Early et al. 2016). In addition to being an entry point for invasive species to the rest of the country, Florida is particularly vulnerable to the establishment of invasive plants due to its tropical/subtropical climate and diverse ecosystems (Simberloff 1997; Pyšek et al. 2017). Management of invasive plants in Florida's conservation areas costs nearly $45 million annually (Hiatt et al. 2019) and invasive species (including plants, insects, and pathogens) cost Florida's agriculture industry at least $179 million annually (Coffman et al. 2001). Identifying potential invaders before or soon after they enter Florida can reduce ecological and economic losses to the state as well as prevent the spread of invasive plants nationally.

Here, we developed a horizon scan approach to create a ranked list of non-native plants that are likely to arrive and establish in Florida and have impacts on native biodiversity, the economy, or human health in the near future. We started with a large initial list of plant taxa that were associated with invasion. We then developed criteria and used publicly available datasets to prioritize taxa for risk assessment. This step builds on previous horizon scans, which were able to assess all taxa on initial lists. We present a ranked list of potential invasive plant threats to Florida, which can be used to inform research, management, and policy aimed at reducing invasive plant impacts.

Methods

This horizon scan was part of the Florida Invasion Threats Horizon Scan, which assessed invasion threats of freshwater and terrestrial plants (reported here), marine taxa, freshwater invertebrates, terrestrial invertebrates, and non-marine vertebrates (Lieurance et al. in review). We adapted and revised the horizon scanning method outlined by Roy et al. (2014, 2015) to develop a ranked list of invasive plant threats and their potential pathways for arrival to the target location (Florida) in the near future (e.g., 5–15 years). We chose this time frame to prioritize upcoming threats, to establish a minimum frequency for updating the horizon scan with new information (once every 5–15 years), and to evaluate risk within current climate conditions (i.e., omitting future climate change scenarios). We kept this time frame in mind by considering current arrival pathways and environmental conditions in the target location.

Expert panel and workshop

We (the authors) formed the expert panel for freshwater and terrestrial plants, providing knowledge of Florida's natural systems, existing invasive plants, relevant policy, and data analysis. Along with experts of other taxonomic groups described above, we convened a workshop for the Florida Invasion Threats Horizon Scan in December 2019. During the workshop, we designed criteria for prioritizing taxa to assess (see Assembling a list) and discuss the rapid risk assessment tool (see Assessing and scoring the taxa).

Assembling a list

Using the horizon scan tool developed by the Centre for Agriculture and Biosciences International (CABI; an inter-governmental not-for-profit organization that provides information and expertise on agriculture and the environment), we generated an initial list of invasive taxa and crop pests (Suppl. material 1). The tool consolidates information from the CABI Invasive Species Compendium and Crop Protection Compendium, which are science-based encyclopedic databases (CABI 2018). Based on these databases, the tool generated a list of 2128 plants and algae that were not known to be present in Florida.

We corrected the list for synonyms and accepted names using (in the order of our assigned authority): the Atlas of Florida Plants (Wunderlin et al. 2019), the Integrated Taxonomic Information System (Integrated Taxonomic Information System 2000), and the Taxonomic Name Resolution Service (Boyle et al. 2015; see Suppl. material 1 for more details). We then identified taxa that were growing in at least one location with similar climate to the target location (Kottek et al. 2006; CABI 2018), not already naturalized in the target location (Wunderlin et al. 2019), not on a local (i.e., Florida) or national noxious weed list, naturalized outside of their native ranges (van Kleunen et al. 2019), and historically weedy (Randall 2017; Fig. 1, Suppl. materials 1, 2). We next used expert opinion to remove two taxa: one taxon that had already been assessed by a panel member and one that was only specified to genus level (Suppl. material 1). Finally, we selected the top 100 most globally common taxa for further assessment (GBIF.org 2022, Suppl. material 1), which was the largest number of taxa that nine assessors could evaluate given 20 hours of assessment time each (and 40 hours for one assessor). Global commonness serves as a proxy for propagule pressure and establishment success (Shah et al. 2012; Blackburn et al. 2015).

Assessing and scoring the taxa

Nine assessors evaluated taxa using a rapid risk assessment tool modified from Roy et al. (2014). First, we used a species not included in the assessment list to evaluate the tool for clarity, timing, and assessment consistency. Then, we completed risk assessments with a standardized set of resources (Suppl. material 3). Because the risk assessments are designed to be completed rapidly, we aimed to spend less than two hours on each taxon.

We identified one or more potential pathways for taxa to arrive in Florida based on an established framework (Hulme et al. 2008; CBD 2014; Harrower et al. 2018). Briefly, the pathways included "release in nature" (intentional release, such as for erosion control), "escape from confinement" (intentional commodity that escapes, such as a horticultural taxon), "transport contaminant" (associated with the transport of a specific commodity, such as a seed contaminant), "transport stowaway" (other forms of unintentional transport, such as through soil on equipment), "corridor" (through human infrastructure linking previously unconnected areas, such as a waterway), and unaided (natural dispersal).

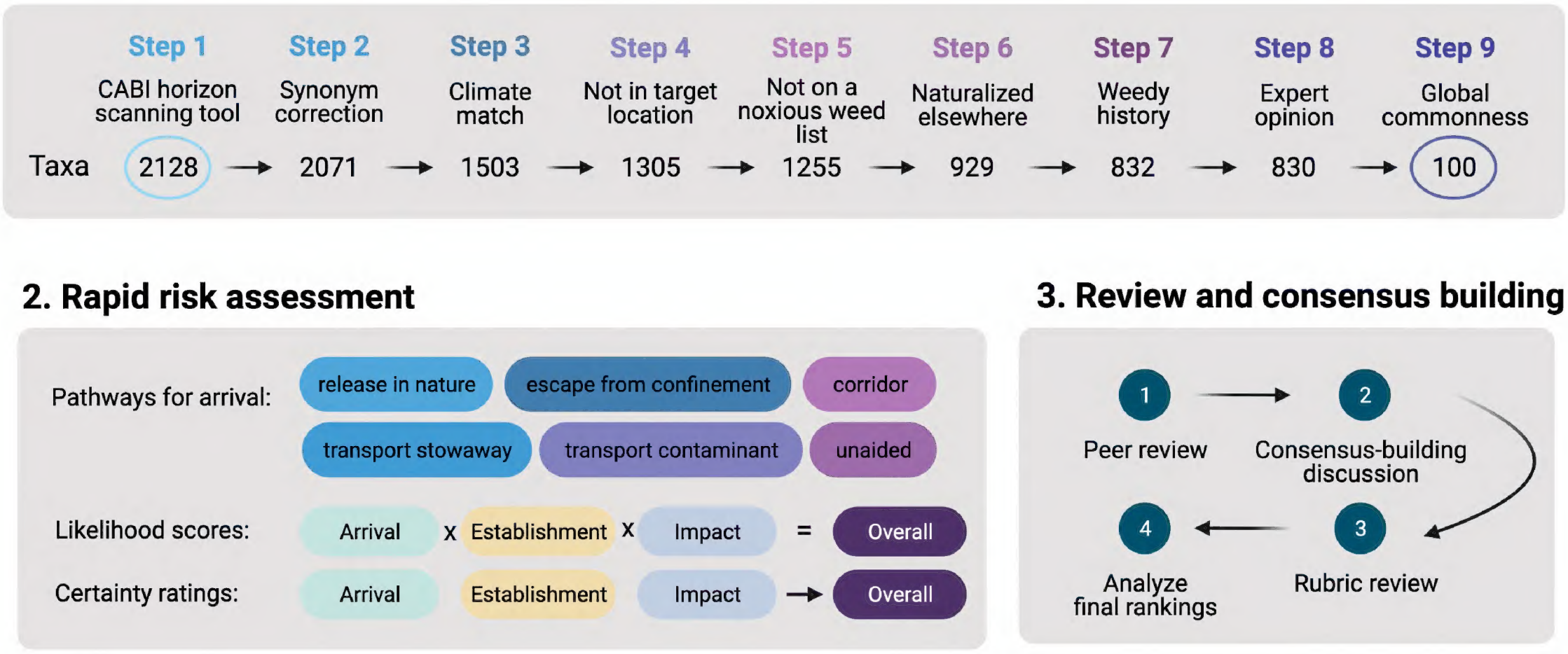

Figure 1. Methods for selecting and evaluating taxa as invasive plant threats for a target location (Florida, United States). Data-based list processing led to the prioritization of 100 taxa for risk assessment. Rapid risk assessments performed by an expert panel included pathways for arrival and likelihood scores and certainty ratings for arrival, establishment, and impact. The three component likelihood scores were multiplied to get an overall score and certainty ratings were roughly averaged to get an overall certainty. Each risk assessment was evaluated with two rounds of review and a consensus-building discussion before the expert panel confirmed taxa rankings.

We scored the likelihoods of arrival, establishment, and negative impacts (environmental, socioeconomic, and human health) on a scale of 1 (very low) to 5 (very high; Fig. 1). To estimate the likelihood of arrival, we considered the current distribution of the taxon, the availability of the taxon for purchase, history of invasion by the taxon in other regions, and the presence of a plausible arrival pathway (Table 1).

To estimate the likelihood of establishment (i.e., developing a self-sustaining population), we considered the distribution and number of records of the taxon within regions with Köppen-Geiger climate zones matching Florida (Table 1). This evaluation expands on the use of Köppen-Geiger climate zones to select taxa for our assessment list, in which records in only one matching location were needed to pass the criterion (Fig. 1). We also considered ecological properties of both the taxon and target location habitats, including time to reproductive maturity, reproduction rate, dispersal mechanism, propagule pressure, tolerance of a broad range of environmental conditions, resource availability, natural enemies, and amount of nurturing required (e.g., weeding, irrigation, fertilization, pest control; Petri et al. 2021). Geographic thresholds for arrival and establishment likelihood scores (Table 1) were chosen based on distance, ease of movement through ground transportation, and low barriers to introduction by travel or mail (USDA APHIS 2017a, b).

To estimate the likelihood of negative impacts, we used a scoring rubric modified from the Invasive Species Environmental Impact Assessment protocol (Branquart 2009), the Environmental Impact Classification of Alien Taxa (Blackburn et al. 2014; Hawkins et al. 2015), and the Socio-Economic Impact Classification of Alien Taxa (Bacher et al. 2018; Table 1). The overall risk score was the product of arrival, establishment, and impact likelihood scores (Fig. 1; Roy et al. 2015). We provided brief justifications for our scores and assigned certainty ratings that ranged from very low (i.e., all scores were equally likely) to high (i.e., could confidently eliminate all other scores). The overall certainty rating was the rating most consistent with three component certainty ratings (Suppl. material 3).

Review and consensus building

Assessments were peer-reviewed by the panel (Suppl. material 1). During the virtual consensus-building meeting, we discussed taxa in descending order of scores and removed one taxon because of ambiguity about whether it was already naturalized in Florida (Suppl. material 1). Because reviewers used a range of criteria for arrival and establishment justifications that were inconsistent across taxa, we created rubrics (Table 1) and reviewed scores again. After confirming overall scores with the panel, we categorized taxa as follows: taxa scoring ≥ 64 (i.e., an average score of 4 for each category of arrival, establishment, and impact) as high risk, taxa scoring ≥ 27 (i.e., an average score of 3 for each category) and < 64 as medium risk, and taxa scoring < 27 as low risk. This process resulted in a final list of 99 taxa that moved through the assessment, review, and analysis steps (Fig. 1).

Table 1. Rubrics for scoring likelihood of arrival, establishment, and impacts of potential invasive plants.

Category	Criteria	Score
Arrival[†]	Closest observation to target location[‡] and closest online seller to target location are outside of region[§].	1
	Closest observation to target location is within region, but not nearby[§], and closest online seller to target location is outside of region.	2
	Closest observation to Florida and closest online seller to target location are within region, but not nearby or closest observation to target location is nearby, but not in target location, and closest online seller to target location is outside region.	3
	Closest observation to target location is nearby, but not in target location, and closest online seller is within region or nearby, but not in target location.	4
	The taxon has been observed or sold within target location.	5
Establishment[†]	No observations in areas with matching Köppen-Geiger (KG) zones to target location[|].	1
	Few observations in one area with matching KG zones to target location.	2
	Many observations in one area or few observations in multiple areas with matching KG zones to target location.	3
	Many observations in multiple areas with matching KG zones to target location.	4
	Criteria for score 4 plus evidence of a biological strategy that aids establishment or evidence of establishment in target location.	5
Impact	Unlikely to cause negative impacts on the native biota or abiotic environment, human well-being, or economic systems.	1
	Likely to cause (a) declines in the performance (e.g., biomass, body size) of native biota, but no decline in native population sizes or (b) income loss, minor health problems, higher effort or expense to participate in activities, increased difficulty in accessing goods, or minor disruption of social activities, but no significant impact on participation in normal activities.	2
	Likely to cause (a) declines in the population size(s) of native species, but no changes to the structure of communities or to the abiotic or biotic composition of ecosystems or (b) changes in the size of social activities, with fewer people participating, but the activity is still carried out. These changes to social activities could be linked to accessibility to the activity area or mild effects to human health (e.g., allergies).	3
	Likely to cause (a) the local or population extinction of at least one native species, leading to reversible changes in the structure of communities, the abiotic or biotic composition of ecosystems or (b) the local disappearance of a social or economic activity from all or part of the area invaded by the alien taxon, collapse of the specific activity, switch to other activities, abandonment of activity without replacement, emigration from region, or moderate effects to human health.	4
	Likely to cause (a) the replacement and local extinction of native species and will produce irreversible changes in the structure of communities and the abiotic or biotic composition of ecosystems or (b) local disappearance of a social or economic activity from all or part of the area invaded by the alien taxon or major effects to human health.	5

[†]Arrival and Establishment rubrics were applied during the second review phase. Scores were adjusted by up to one point based on additional information in the assessments.

[‡]target location = Florida, United States; observations based on GBIF.org (2020) or information provided by the assessor or reviewer.

[§]For our purposes, "region" is contiguous United States and "nearby" are the states of Georgia, Alabama, South Carolina, North Carolina, Tennessee, and Mississippi.

[|]Observations based on GBIF.org (2020) or information provided by the assessor or reviewer. Florida's Köppen-Geiger zones include Af, Am, Aw, and Cfa (Kottek et al. 2006).

Analysis of risk scores

We evaluated whether peer-review and consensus building significantly affected overall risk scores with a paired two-sample *t*-test (before vs. after). We also evaluated how assessors and characteristics of the taxa affected overall risk scores. We fit a generalized linear regression with a negative binomial error structure to the overall risk scores with the expert who completed the assessment ($N = 9$), expert certainty about the overall score (very low, low, medium, or high), whether the typical habitat is terrestrial or

aquatic, the number of records in the United States, and the year of the earliest occurrence record in the United States (cultivated, naturalized, and otherwise) as independent variables. We assumed the number of records and earliest record were proxies for propagule pressure (the former metric), residence time (the latter metric; Pyšek et al. 2009), and existing information in the literature, internet, and held by experts (both metrics). We used the package 'rgbif' (Chamberlain et al. 2021) to extract all Global Biodiversity Information Facility (GBIF) records in the United States for each taxon, selecting records that had coordinates and no geospatial issues (GBIF.org 2021). Number of records and earliest record from this dataset were centered and scaled and were not significantly correlated with each other ($r = 0.04$, $P = 0.68$). We fit the model using the 'MASS' package (Venables and Ripley 2002), evaluated the fit using the 'DHARMa' package (Hartig and Lohse 2020), tested the significance of each independent variable using likelihood ratio tests, and compared estimated marginal means of factor levels with the Tukey method using the 'emmeans' package (Lenth et al. 2021). All analyses were conducted in R version 4.0.2 (R Core Team 2020).

Plant families and geographic ranges

We evaluated whether plant taxonomic families were under- or overrepresented in the CABI plant list and in the final list using a resampling procedure (Daehler 1998). We first extracted all accepted species names and their family names from The Plant List using the 'taxize' package (Chamberlain and Szoecs 2013, TPL 2013), resulting in a dataset of 373,847 taxa. The CABI list contained 158 families (with 2091 taxa) in The Plant List (vascular plants and bryophytes). We re-sampled 2091 taxa without replacement from The Plant List dataset 10,000 times. Taxa were replaced between iterations and we counted the number of taxa per family at each iteration. We set the threshold for statistical significance to $P < 0.0003$ (0.05 divided by the number of families, consistent with a Bonferroni correction; Daehler 1998). Therefore, if the number of taxa sampled from a family was greater (less) than or equal to the number of taxa from that family in the CABI list in fewer than three iterations, we considered the family overrepresented (underrepresented) in the CABI list. We repeated this procedure with different values for the final list: 34 families with 98 taxa, 1,000 iterations, $P < 0.0015$, and families with one or fewer iterations.

To evaluate the native and introduced ranges of taxa in the final list, we researched their distributions using the Plants of the World database (for 95 of the 99 taxa; POWO 2021), the CABI Invasive Species Compendium (CABI 2021), the Global Compendium of Weeds (Randall 2017), and GBIF (GBIF.org 2020). We summarized and mapped distributions using the World Bank Development Indicator regions in the 'countrycode' package (Arel-Bundock et al. 2018). One species, *Aegagropila linnaei*, was omitted from the map because we were unable to clearly define its native range.

Data availability

Data and code are available at https://doi.org/10.5281/zenodo.6211243.

Results

Analysis of risk scores

We found no significant difference in the means of overall risk scores before and after peer-review and consensus building (t = -1.41, 95% CI = -4.43–1.61, df = 97, P = 0.357) with an average score (± SE) of 21.3 ± 2.1 before and 22.7 ± 2.1 after. However, the overall risk scores of 14 taxa increased enough to move them into a higher risk category, with one taxon (*Avena fatua*) moving two categories higher. Additionally, the overall risk scores of ten taxa decreased enough post-review and consensus building to move them into a lower risk category, with one taxon (*Campylopus introflexus*) moving two categories lower. These larger changes in overall risk scores resulted from assessors reconsidering how to interpret available information following consensus building and rubric review (Table 1, Suppl. material 3).

There was strong evidence that the assessor and certainty level affected the overall risk score (Table 2). Four out of 36 pairwise comparisons of assessors were significantly different with $P < 0.05$. Taxa with higher overall certainty ratings also had higher overall risk scores (Fig. 2C). Taxa with earlier first records in the United States received higher overall risk scores than taxa with later first records (Fig. 3A, Table 2). Taxa with more records in the United States did not receive significantly higher overall risk scores (Table 2), although there was a positive trend (Fig. 3B).

Plant families and geographic ranges

Four families were significantly overrepresented in the final list of 99 taxa compared to the number of accepted species in the family (Suppl. material 4): Juncaceae (3 taxa out of 581 accepted species), Poaceae (21 taxa/11883 accepted species), Polygonaceae (4 taxa/1584 accepted species), and Rosaceae (7 taxa/5325 accepted species). These four families were also significantly overrepresented in the CABI list (Suppl. material 5): 21 taxa (1% of the CABI list) were in Juncaceae, 226 taxa (11%) were in Poaceae, 37 taxa (2%) were in Polygonaceae, and 80 taxa (4%) were in Rosaceae. None of the families present on the final list were significantly underrepresented.

The majority (93%) of taxa on the final list had native ranges that included Europe and Central Asia, 75% included the Middle East and North Africa, and 67% included East Asia and the Pacific (Fig. 4A). Other regions were included in 43% or fewer of the taxa's native ranges. The United States was included in the native ranges of

Table 2. Model summary of overall risk scores, evaluated with likelihood ratio tests of nested models.

Variable	χ^2	df	P
Assessor	27.02	8	< 0.001
Certainty	21.40	3	< 0.001
Earliest U.S. record	3.85	1	0.05
Records in United States	1.67	1	0.20
Habitat (terrestrial vs. aquatic)	0.07	1	0.79

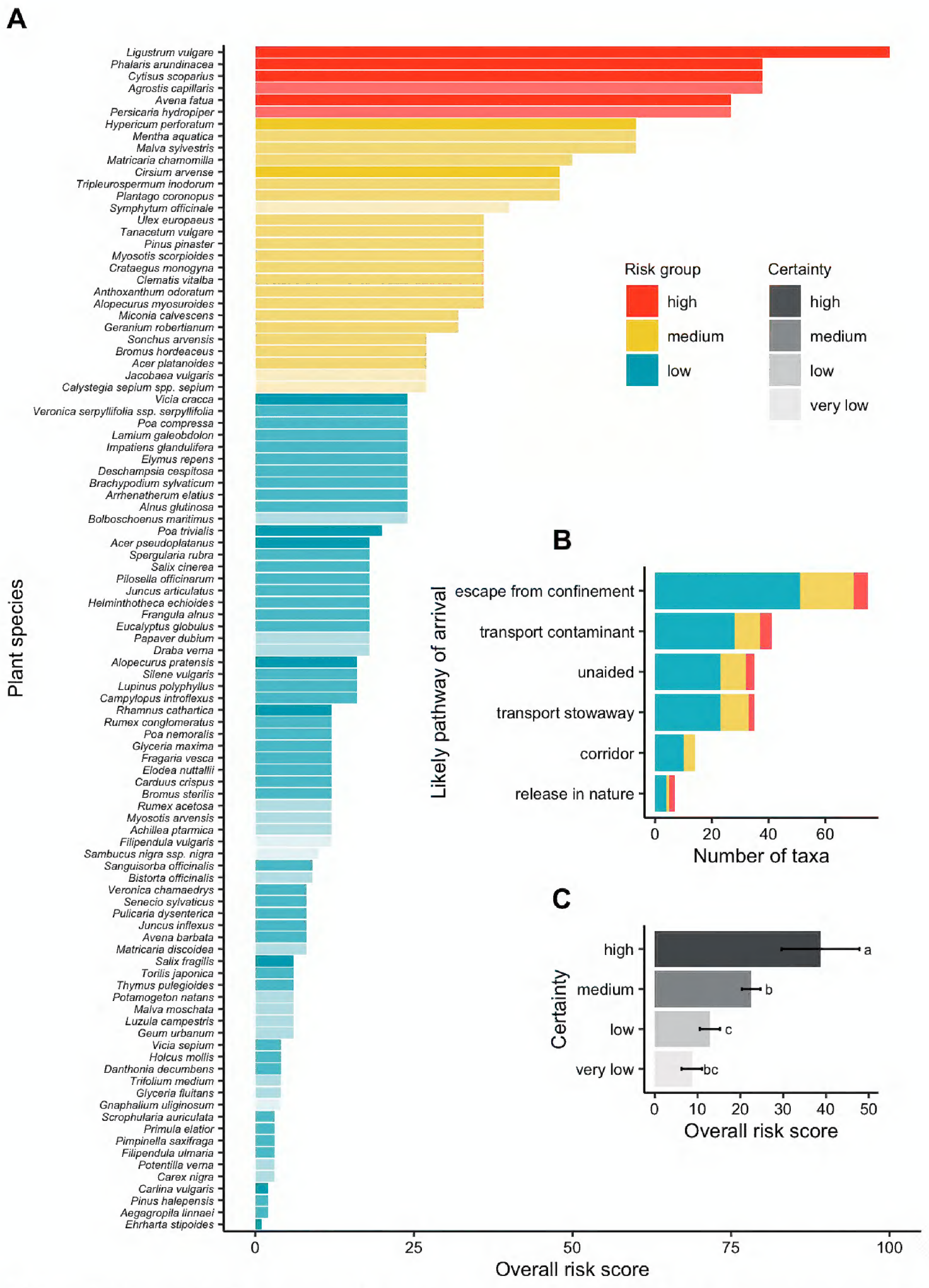

Figure 2. Overall likelihood scores from the horizon scan of potential invasive plant threats to Florida **A** the overall risk scores for 99 taxa, divided into groups of high risk (score ≥ 64), medium risk (27 ≤ score < 64), and low risk (score < 27) and shaded by overall certainty rating **B** the number of taxa associated with each of the pathways of arrival. Multiple pathways could be assigned to a single taxon. **C** the relationship between certainty and the overall risk score, averaged across all taxa. Letters above bars indicate significant differences in overall risk score among certainty ratings with $P < 0.05$.

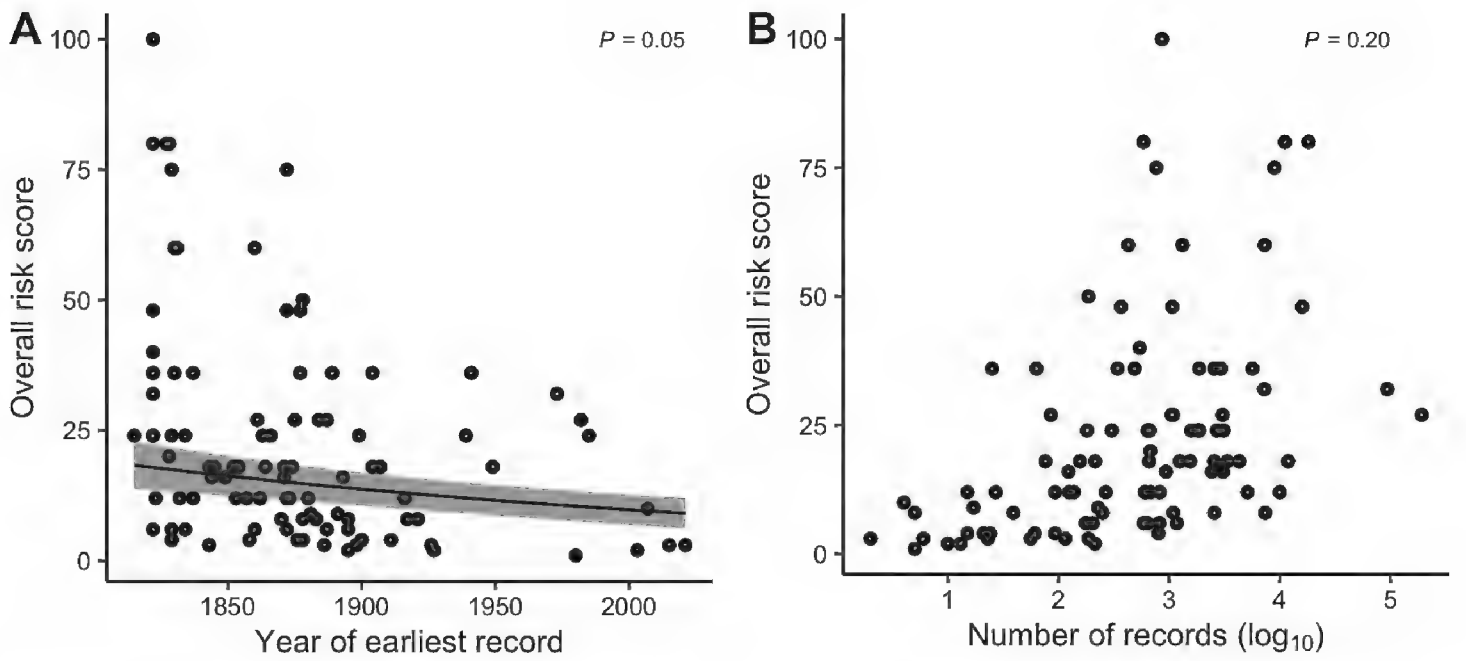

Figure 3. Earliest record and number of records. The overall risk score and **A** the year of the earliest record in the United States and **B** the number of records (displayed on a $\log_{10}$ scale for clarity) in the United States for the 99 taxa on the final list. Points represent data while line and shading represent model-estimated mean ± SE.

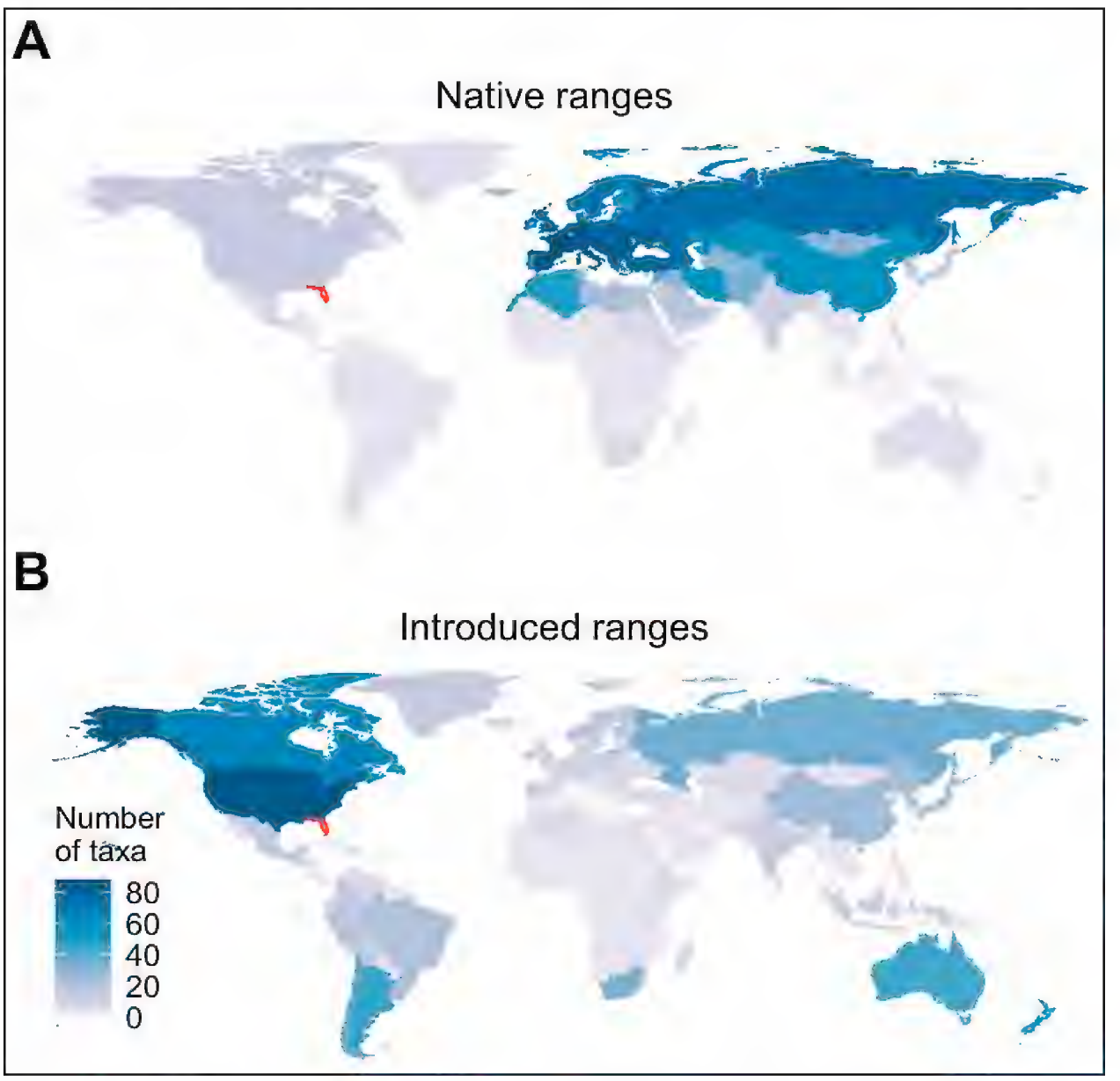

Figure 4. Ranges of taxa **A** native and **B** introduced ranges of the final list of taxa generalized at the country level. Countries with darker shades indicate a greater number of taxa native or introduced to the area. The target location (Florida) is in red.

11 taxa: *Bolboschoenus maritimus*, *Carex nigra*, *Deschampsia cespitosa*, *Elodea nuttallii*, *Fragaria vesca*, *Geranium robertianum*, *Juncus articulatus*, *Lupinus polyphyllus*, *Phalaris arundinacea*, *Potamogeton natans*, and *Sanguisorba officinalis*. Although some native populations of *P. arundinacea* exist in North America, most populations are Eurasian genotypes (Jakubowski et al. 2014). The remaining ten taxa are native to some U.S. states, but are not in the target location (Florida; USDA 2019). The majority (89%) of the taxa on the final list have been introduced to North America (Fig. 4B). This region was followed closely by East Asia and the Pacific (79%), Europe and Central Asia (71%), and Latin America and the Caribbean (69%). Other regions were included in 40% or fewer of the taxa's introduced ranges.

High risk taxa

Six plant taxa received risk scores of at least 64 (Figs 2, 5), indicating that they are likely to invade Florida in the near future. We had high certainty about the risk scores for four taxa: *Ligustrum vulgare*, *Cytisus scoparius*, *Phalaris arundinacea*, and *Avena fatua*. We had medium certainty for the other two taxa: *Agrostis capillaris* and *Persicaria hydropiper*. Three were considered very likely to arrive in Florida (arrival score = 5 out of 5): *L. vulgare*, *A. fatua*, and *P. hydropiper.* This conclusion was based on herbarium specimens indicating historic, but not current, presence in Florida; observations of presence without naturalization within the last 20 years; and records of seeds sold within the United States at the time of the assessment (Suppl. material 3). All six taxa were considered very likely to establish in Florida (establishment score

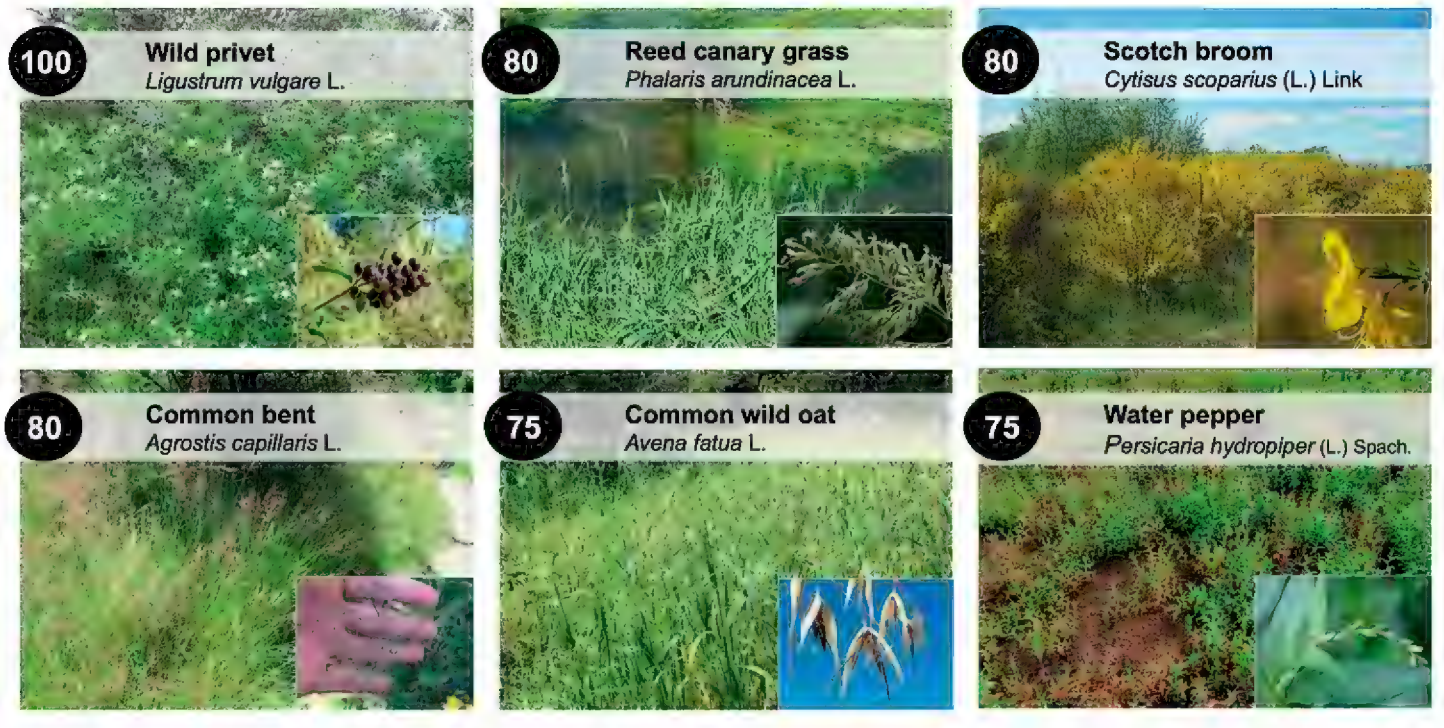

Figure 5. The six taxa that were designated as high risk for invasion in Florida. Overall risk scores are in black circles (maximum possible score is 125). (Photos: Meneerke bloem, Isidre blanc, Andreas Eichler, Stefan.lefnaer, CC BY-SA 4.0; Robert Flogaus-Faust, CC BY 4.0; Rasbak, CC BY-SA 3.0; Willow, CC-BY 2.5; Mary Joyce, Katrice Baur, scottq1, rae117, CC BY-NC 4.0; Christian Grenier, CC0 1.0).

= 5 out of 5) because they occur in other regions of the world with climates similar to Florida's and in some cases, they are known to have high reproductive capacity (Suppl. material 3). Four taxa were considered likely to cause loss of native species, loss of social or economic activity, or moderate human health effects (impact score = 4 out of 5): *L. vulgare*, *C. scoparius*, *P. arundinacea*, and *A. capillaris*. Impacts of the high risk taxa included suppressing native vegetation through competition, producing pollen that can be a human allergen, and reducing crop yields (Table 3, Suppl. material 3). Information about the six taxa from a handful of sources can help inform potential future policy actions (Table 3): the taxa have global distributions; they have cultural and economic uses that have facilitated their introduction to new regions; they are managed through various, often integrated, approaches; and they are included in non-Florida U.S. state noxious weed lists or laws.

Table 3. Summary of the six high risk species using three of the main references used in rapid risk assessment.

Species	Native range[†]	Introduced countries[‡]	Common uses[§]	Potential impacts[§]	Management approaches[§]	States listed[|]
Ligustrum vulgare	Europe, western Asia, northern Africa	Argentina, Australia, Brazil, Canada, New Zealand, South Africa, United States	landscape (planted as a hedge or border), medicinal	host crop pests, compete with native plants, pollen allergens, poisonous berries	mechanical (pulling, digging, cutting), herbicides	11
Phalaris arundinacea	Asia, Europe, Central America, North America[¶], southern/eastern/northern Africa	Ethiopia, Kenya, Tanzania, Uganda	erosion control, fodder crop, fiber, ornamental, biofuel	obstruct waterways, compete with native plants, reduce wildlife habitat quality	integrated control, burning, discing, mowing, herbicides	10
Cytisus scoparius	Europe	Argentina, Australia, Bolivia, Brazil, Canada, Chile, China, India, Iran, Japan, New Zealand, South Africa, United States	ornamental, medicinal, nurse plant	compete with native plants, facilitate other invasive species, alter nutrient and water availability	integrated control, burning, grazing, mulching, pulling, cutting, herbicides, biological control	14
Agrostis capillaris	central/western/southwestern Asia, Europe, North Africa,	Argentina, Australia, Bhutan, Brazil, Canada, Chile, Greenland, India, New Zealand, Saint Helena, Saint Pierre and Miquelon, South Georgia and the South Sandwich Islands, United States	turf grass (lawns and golf), fodder, pasture, erosion control, landscape rehabilitation	competes with native plants, indirectly reduce moth population sizes through loss of native plants, pollen allergens	crop rotations, pulling, herbicides	5
Avena fatua	Central Asia	Canada, United States (present in 74 other countries, but "introduced" status not provided)	fodder, forage, gene source for disease resistance, medicinal	reduce crop yields	straw burning, crop rotation, herbicides, soil cultivation, soil solarization	4
Persicaria hydropiper	Europe	"introduced" status not provided, but present in 48 countries	culinary, medicinal	crop and pasture weed	herbicides	1

[†]Geographic regions where the taxon is native (CABI 2021, Native Plant Trust 2021).

[‡]Countries where the taxon has been introduced (CABI 2021).

[§]Uses, impacts, and management approaches in CABI database (2021). This information was used, along with other sources, in rapid risk assessments.

[|]U.S. states in which the taxon is included in a prohibited list or law (EDDMapS 2021).

[¶]See Plant families and geographic ranges section for more details.

Medium risk taxa

Twenty-three taxa received medium risk scores (27 ≤ score < 64; Fig. 2). Two taxa, *Matricaria chamomilla* and *Symphytum officinale*, were considered very likely to arrive in Florida (arrival score = 5) because they had records in Florida, including two for *S. officinale* that suggested escape (Suppl. material 3). Both taxa were also considered very likely to establish in Florida (establishment score = 5) and cause declines in native species' performances or minor human social, economic, or health problems, but not more negative impacts (impact score = 2). Three taxa, *Hypericum perforatum*, *Malva sylvestris*, and *Mentha aquatica*, were considered likely to arrive in Florida (arrival score = 4), very likely to establish in Florida (establishment score = 5), and likely to cause declines in native species' population sizes or human participation in social activities (impact score = 3). All five taxa are sold as ornamental plants within the United States and have been reported in the southeastern United States in the past 20 years (Suppl. material 3). We had high certainty about the scores of two taxa (including *H. perforatum*), medium certainty about the scores for 18 taxa, and low certainty about the scores for three taxa (including *S. officinale*).

Low risk taxa

Seventy taxa received low risk scores (< 27; Fig. 2). *Poa trivalis* was considered very likely to arrive in Florida (arrival score = 5) because it is in the southeastern United States, has been used in at least one research experiment in Florida, and is planted in golf courses in the southeast both intentionally and unintentionally (seed contaminant). *Poa trivalis*, however, is unlikely to establish in Florida (establishment score = 2) and have severe impacts (impact score = 2). *Sambucus nigra* ssp. *nigra* was considered very likely to establish in Florida (establishment score = 5) because the species *Sambucus nigra* occurs in multiple locations with climate similar to Florida's (Suppl. material 3). However, the subspecies has few recorded occurrences globally, which led to very low certainty about the establishment score. In addition, *Sambucus nigra* ssp. *nigra* was considered very unlikely to arrive in Florida (arrival score = 1) and likely to cause declines in native species' performances or minor human social, economic, or health problems, but not more negative impacts (impact score = 2). We had high certainty about the scores of eight taxa, medium certainty about the scores of 43 taxa, low certainty about the scores of 16 taxa, and very low certainty about the scores of three taxa.

Pathways of arrival

The most likely pathway of arrival for the taxa on the final list was escape from confinement (Fig. 2B). Taxa are also likely to arrive in Florida as transport contaminants, transport stowaways, or with unaided dispersal. It is less likely that plants will arrive through intentional release into nature or through a constructed corridor.

Discussion

Our horizon scan of invasive plant threats to Florida identified six taxa that have a high risk of becoming invasive in the state in the near future (5–15 years). The horizon scanning process helped us identify taxa that should undergo more thorough risk assessments and potentially receive policy restrictions or research priority. Our reliance on existing databases allowed us to quickly evaluate many taxa in a manner than can be applied to future horizon scans. Further, we used this case study to assess biases in the horizon scan process that should be taken into consideration in future horizon scans of invasive plants.

Although we used databases to reduce the number of taxa on our list, it was necessary to use expertise to perform rapid risk assessments, review, and consensus building. These expert-based processes are therefore not repeatable, but we aimed to increase transparency by providing the assessments and reviews (Suppl. material 3). The identity of the assessor significantly affected the overall risk scores. Two assessors who had 3–8 years of risk assessment experience scored taxa higher on average than two assessors who had less than one year of risk assessment experience. Because our sample size of assessors is small, we are unsure whether this outcome is coincidental (due to the taxa assessed by these individuals) or due to assessor experience. To address differences in experience, future horizon scans could calibrate scores among assessors with a set of test taxa, a more rigorous approach than our calibration with a single taxon, or derive composite scores from multiple assessors, for example through structured expert judgement (Wittmann et al. 2015). Discrepancies in experience highlight the importance of rubrics, peer review, and consensus building; although experience may have influenced assessors during the risk assessment phase, all assessors agreed on the final ranking of taxa.

Overall risk scores were positively related to overall certainty ratings. We hypothesize that this occurred because more available data can contribute to higher certainty and provide more evidence that a taxon may arrive, establish, or have impacts. Similarly, risk scores were negatively related to the year of the earliest U.S. record. We hypothesize that taxa with earlier and more records of occurrence in the United States are likely to be better represented in English-language texts than less common or more recently detected taxa, leading to more evidence for arrival, establishment, and impacts. Efforts to synthesize and standardize information about invasive species (Simpson et al. 2019; CABI 2021) could reduce these potential sources of bias. The relationships between risk scores and earliest record (negative) and number of records (positive) may also indicate that taxa with longer residence time and larger population sizes, respectively, have greater risk of arrival, establishment, and impact (Pyšek et al. 2009).

We evaluated taxonomic and geographic biases in the final horizon scan list and taxonomic biases in the initial CABI list. These biases may indicate shared characteristics of invasive plants or cultural biases in the CABI databases. While we cannot distinguish between these two causes, we look to previous studies for insights. The families Juncaceae (rushes), Poaceae (grasses), Polygonaceae (knotweeds), and Rosaceae (roses) were significantly overrepresented in both the final horizon scan list and the initial

CABI list compared to the number of taxa in these families. These families are similarly overrepresented in global lists of naturalized plants (Daehler 1998; Pyšek et al. 2017). The overrepresented families may indicate shared characteristics of invasive plants. Taxa in these families are characterized by traits that can aid invasion, including high reproduction, broad environmental tolerance, and high human use frequency (Hummer and Janick 2009; Canavan et al. 2019; Ashby et al. 2020). In addition, mis-identified invasive rushes and grasses may go undiscovered for long periods, allowing them to establish self-sustaining populations before being controlled (Scott and Hallam 2003). Such general trends can help identify families on which to concentrate risk assessment resources.

Most of the taxa that made our final list were native to Europe, Asia, and North Africa. This result is likely a combination of shared characteristics of invasive plants and cultural biases in the initial CABI list. Europe is the native range for a disproportionately high number of naturalized plant species relative to the number of native plant species (van Kleunen et al. 2015), which may be influenced by plant adaptations to European pastoralism and cultivation—practices that have been widely adopted (MacDougall et al. 2018)—and historical exchange between Europe and other geographic regions (Pyšek et al. 2015). Temperate Asia is also a major source of global naturalized plant species (van Kleunen et al. 2015). Because Florida's Köppen-Geiger climate zones most consistently overlap with Central and South America, central Africa, and southern and eastern Asia (Kottek et al. 2006), our final list likely omits key high risk taxa. Further, the scoring systems for arrival and establishment likelihoods may better estimate risk by including key locations outside of the contiguous U.S., such as Hawaii, Puerto Rico, and the U.S. Virgin Islands. Future horizon scans could focus more on taxa from geographic regions with a similar climate to the target location and strong trade and tourism ties. Although we did not evaluate the geographic ranges of taxa on the initial CABI list, our results from the final list indicate that this analysis could be an important initial step of the horizon scan process to identify whether invasive or naturalized species lists from underrepresented geographic regions need to be obtained.

Overall scores were calculated by multiplying likelihoods of arrival, establishment, and impact (Roy et al. 2015). By equally weighting these three processes, we assumed that each was crucial to a taxon becoming invasive (Blackburn et al. 2011, 2014; Bacher et al. 2018). Four taxa (*Ligustrum vulgare*, *Cytisus scoparius*, *Phalaris arundinacea*, and *Avena fatua*) had high overall risk scores with high certainty. Although we did not independently validate these results, staff at the University of Florida (including and trained by one of the authors) assessed these taxa with a more rigorous 49-question predictive tool and found them all to be high invasion risks (University of Florida, Institute of Food and Agricultural Sciences 2018). In our horizon scan, two taxa (*Agrostis capillaris* and *Persicaria hydropiper*) had high overall risk scores, but medium certainty. Because we were unsure how *A. capillaris* would fare in competition with native Florida grasses, competition studies could increase certainty. Similarly, agricultural impact studies of *P. hydropiper*, which interferes with crops and grazing in other regions, could increase certainty about the risk of this taxon. Taxa with high overall risk scores are included in noxious weed lists or laws for 1–14 states (EDDMapS 2021), raising

the question of whether they have already arrived in Florida, but failed to establish. While we considered many environmental factors and plant traits in our assessment of establishment likelihood, establishment experiments may be valuable in informing how much resources should be allocated to preventing invasion of these taxa. On the other hand, the arrival and establishment of these taxa in Florida may be in a lag phase (Taylor and Hastings 2005; Aiko et al. 2010).

We identified "escape from confinement" as the most likely pathway for taxa on our final list to arrive in Florida's natural areas, which is consistent with a global analysis of invasive plants (Hulme et al. 2008). This pathway includes escape from agriculture, botanical gardens, forestry, research facilities, horticulture, and ornamental purposes other than horticulture (CBD 2014). Domestication can select for traits that increase invasion risk, including fast growth rates, high fecundity, and the ability to hybridize (Petri et al. 2021). However, selection for traits that reduce invasion risk and do not interfere with the commercial purposes of plants could help prevent escape from confinement (Petri et al. 2021).

Taxa on our final list were also likely to arrive in Florida's natural areas as transport contaminants or transport stowaways. Florida's seaports are some of the most active in the country (U.S. Army Corps of Engineers 2018), hosting international and domestic trade, as well as millions of cruise passengers (Florida Department of Transportation 2017). Florida is also a top tourist destination, attracting well over 100 million visitors each year (VISIT FLORIDA 2020). These high movement rates provide ample opportunities for plant propagules to enter the state. The risk of introducing taxa through trade routes, however, can be mitigated by identifying steps in the process of importing, processing, and storing goods that can be modified to reduce plant survival (Hulme 2009).

This horizon scan of invasive plant threats to Florida provides a first step in reducing the impacts of invasive species on Florida's natural systems. Like other horizon scans of potential invasive species, the generated list informs future research efforts and policy (e.g., Matthews et al. 2014; Roy et al. 2014; Gallardo et al. 2016; Lucy et al. 2020). Our horizon scan builds on previous invasive species horizon scans, however, in important ways. First, we began with a list of 2128 potential invasive taxa, which was too large a list to perform rapid risk assessments (approximately 2 hours each) in a reasonable timeline (approximately one year between initial workshop and all taxa consensus building; Lieurance et al. in review). We therefore developed data-based criteria to filter the list to 100 taxa. The databases and code we used are publicly available (Suppl. material 1, Kendig et al. 2022) and could be used for other horizon scans of potential invasive plants. Second, the rapid risk assessments and peer reviews led to enough consensus among experts that our final rankings relied entirely on scores from that process (e.g., in contrast to Roy et al. 2014; Lucy et al. 2020). Consensus building led to important methodological changes (i.e., removing a taxon with too much uncertainty, revisiting assessments with arrival and establishment rubrics), but did not directly alter the rankings. A major advantage of this approach is that the rapid risk assessment tool and rubric can increase transparency of the horizon scan process, especially as they become more refined with future horizon scans.

Conclusion

Here we presented a horizon scan of 2128 plant taxa, identifying six with a high invasion risk for Florida in the near future and 93 with medium or low invasion risk. The horizon scan process therefore can potentially reduce the number of taxa requiring thorough risk assessments by three orders of magnitude. The results provide researchers, regulators, and private and public land managers with a practicable list of high risk taxa to focus on. Given the substantial impacts and costs of invaders in Florida, the ability to differentiate and focus efforts on high probability threats is critical.

Acknowledgements

We thank Dale Laughinghouse and Seokmin Kim for help with processing the list, Julie Lockwood and Helen Roy for guidance on the horizon scan process, and all other participants of the Florida Invasion Threats Horizon Scan for constructive discussions. We thank Jane Molofsky, Gerry Moore, Curtis Daehler, and an anonymous reviewer for helpful feedback on the manuscript. Fig. 1 created with BioRender.com. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

We thank the Florida Fish and Wildlife Conservation Commission and UF/IFAS Dean for Research for funding this project.

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Supplementary material 1

Methods S1

Authors: Amy E. Kendig, Susan Canavan, Patti J. Anderson, S. Luke Flory, Lyn A. Gettys, Doria R. Gordon, Basil V. Iannone III, John M. Kunzer, Tabitha Petri, Ian A. Pfingsten, Deah Lieurance

Data type: Supplementary methods

Explanation note: Methods for trimming the list of potential invasive species based on several criteria.

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Link: https://doi.org/10.3897/neobiota.74.83312.suppl1

Supplementary material 2

Table S1

Authors: Amy E. Kendig, Susan Canavan, Patti J. Anderson, S. Luke Flory, Lyn A. Gettys, Doria R. Gordon, Basil V. Iannone III, John M. Kunzer, Tabitha Petri, Ian A. Pfingsten, Deah Lieurance

Data type: Horizon scan criteria.

Explanation note: Potential invasive plant species provided by the CABI Horizon Scan Tool, their synonyms, and their values for criteria described in Suppl. material 1.

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Link: https://doi.org/10.3897/neobiota.74.83312.suppl2

Supplementary material 3

Table S2

Authors: Amy E. Kendig, Susan Canavan, Patti J. Anderson, S. Luke Flory, Lyn A. Gettys, Doria R. Gordon, Basil V. Iannone III, John M. Kunzer, Tabitha Petri, Ian A. Pfingsten, Deah Lieurance

Data type: Rapid risk assessments.

Explanation note: Reviewed rapid risk assessments of the 99 plant species in the final list, ordered by overall score.

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Link: https://doi.org/10.3897/neobiota.74.83312.suppl3

Supplementary material 4

Table S3

Authors: Amy E. Kendig, Susan Canavan, Patti J. Anderson, S. Luke Flory, Lyn A. Gettys, Doria R. Gordon, Basil V. Iannone III, John M. Kunzer, Tabitha Petri, Ian A. Pfingsten, Deah Lieurance

Data type: Statistical results.

Explanation note: Test of under- or overrepresentation of plant families in the final horizon scan list based on resampling of accepted species from The Plant List database.

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Link: https://doi.org/10.3897/neobiota.74.83312.suppl4

Supplementary material 5

Table S4

Authors: Amy E. Kendig, Susan Canavan, Patti J. Anderson, S. Luke Flory, Lyn A. Gettys, Doria R. Gordon, Basil V. Iannone III, John M. Kunzer, Tabitha Petri, Ian A. Pfingsten, Deah Lieurance

Data type: Statistical results.

Explanation note: Test of under- or overrepresentation of plant families in the initial CABI list based on resampling of accepted species from The Plant List database.

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Link: https://doi.org/10.3897/neobiota.74.83312.suppl5